SPACECRAFT TEMPERATURE CONTROL
BY THERMOSTATIC FINS-TEST PREPARATION

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INTRODUCTION

This report is for the six months period from June 1, 1964 through December 1, 1964 on the work done under NASA grant NsG-454, Extension 1. The main topic of this grant was the development and analysis of a spacecraft thermal control system and this system has been described completely in two previous semi-annual reports to the NASA organization. In this report the discussion will be concerned mainly with a test system which has been designed and constructed for testing in the thermal space simulator at Goddard Space Flight Center. In the following material the construction of the test section, the construction of the test system, the test system analysis, and the predicted results from the test section will be described.

1. TEST SECTION CONSTRUCTION

In order to prove the analytical results obtained in the previous investigations, a test section was designed for actual testing of the spacecraft system in the simulated outerspace environment. The assumptions on which the previous analysis was based and which had to be met by the model were: (1) the walls must be specularly reflecting walls, (2) the base should be a diffuse white material, and (3) the fins should be straight at about 150°F. From information obtained from the grantor, it was determined that the size of the test system should be approximately

1 square foot. Therefore, a 1 square foot brass plate was chosen as the base upon which to mount the fins. The fins were assumed in the analysis to be constructed of a bimetallic material which consisted of a Invar low-expansion side material and a high-expansion side material which had manganese as the primary alloying ingredient. These fins were assumed to be 0.003 inch thick and for the 1 square foot plate section it was decided the fins should be made two inches in length with a spacing of two inches between adjacent fin layers. The first problem involved in the construction of the test system was to shape the material in such a way that the fins would be straight or vertical at approximately 150°F. As the material was delivered, it had only a slight longitudinal curvature and a strong crossbow or a curvature in the two inch dimension of the material. Initially a rolling device was constructed in the hope that this could be used to shape the fins but rolling did not produce the desired fin shape. Since rolling did not work, a method involving heat treatment was devised and this system was the ultimate system which was used in fin shaping. Basically the heat treatment method consisted of the rigid application of the fin material to a curved mandrel and then heat treating to obtain the proper curvature. Several trials at different temperatures and with different mandrel shapes were made and the final shape was obtained by wrapping the strip tightly around a piece of tube with an outer diameter of about two inches and heating for about two hours at 370°F. This resulted in approximately the correct curvature in the longitudinal direction or the length of the fin material; however, the fin material still had the crossbow in it which had to be removed. After cutting the fins from the long two-inch wide material, the fins were

again wrapped around about a two-inch diameter mandrel such that the direction of bending was opposite to the direction of the crossbow and they were then heated in this position for an hour at 250°F. These two heat treatments resulted in a fin which had the correct curvature to be used on the test surface. The completed fins were cut into a two and a quarter inch length and 3/16 of an inch on one end was bent backwards in order to avoid the crossbowing effect which develops as the temperature of the fins increases above the ambient temperature. This is shown in Figure 1 where a typical fin with the upper end bent backward is illustrated. In this case,

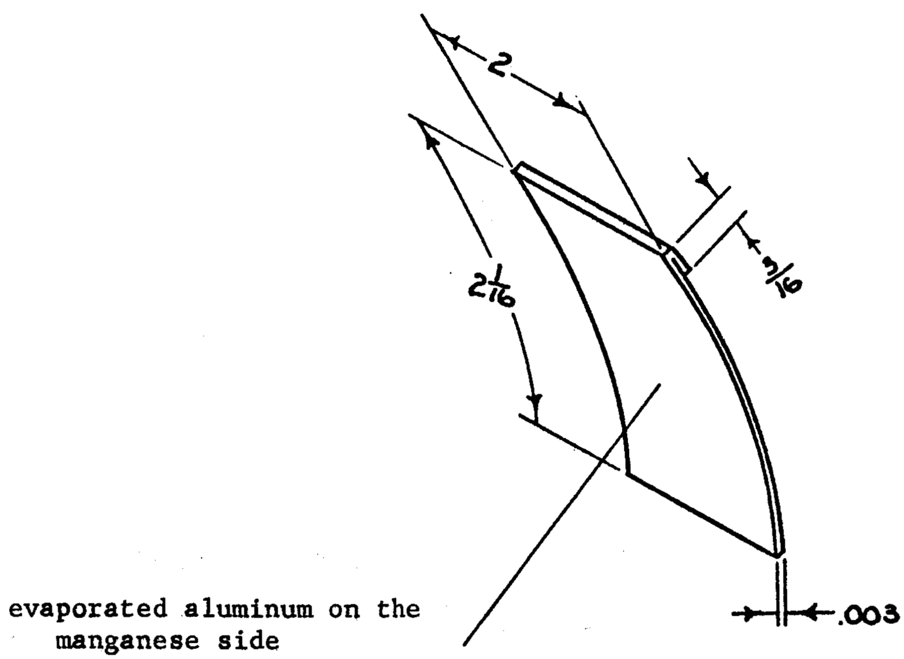

Figure 1
Typical Fin

the connotation of bent backwards means that the fin material was bent in the direction towards the Invar side or low-expansion side. The fins as shown in Figure 2 have the bend which they normally would have at room temperature which of course for these fins is a relatively low temperature. After bending the 3/16 inch strip back along the top of the

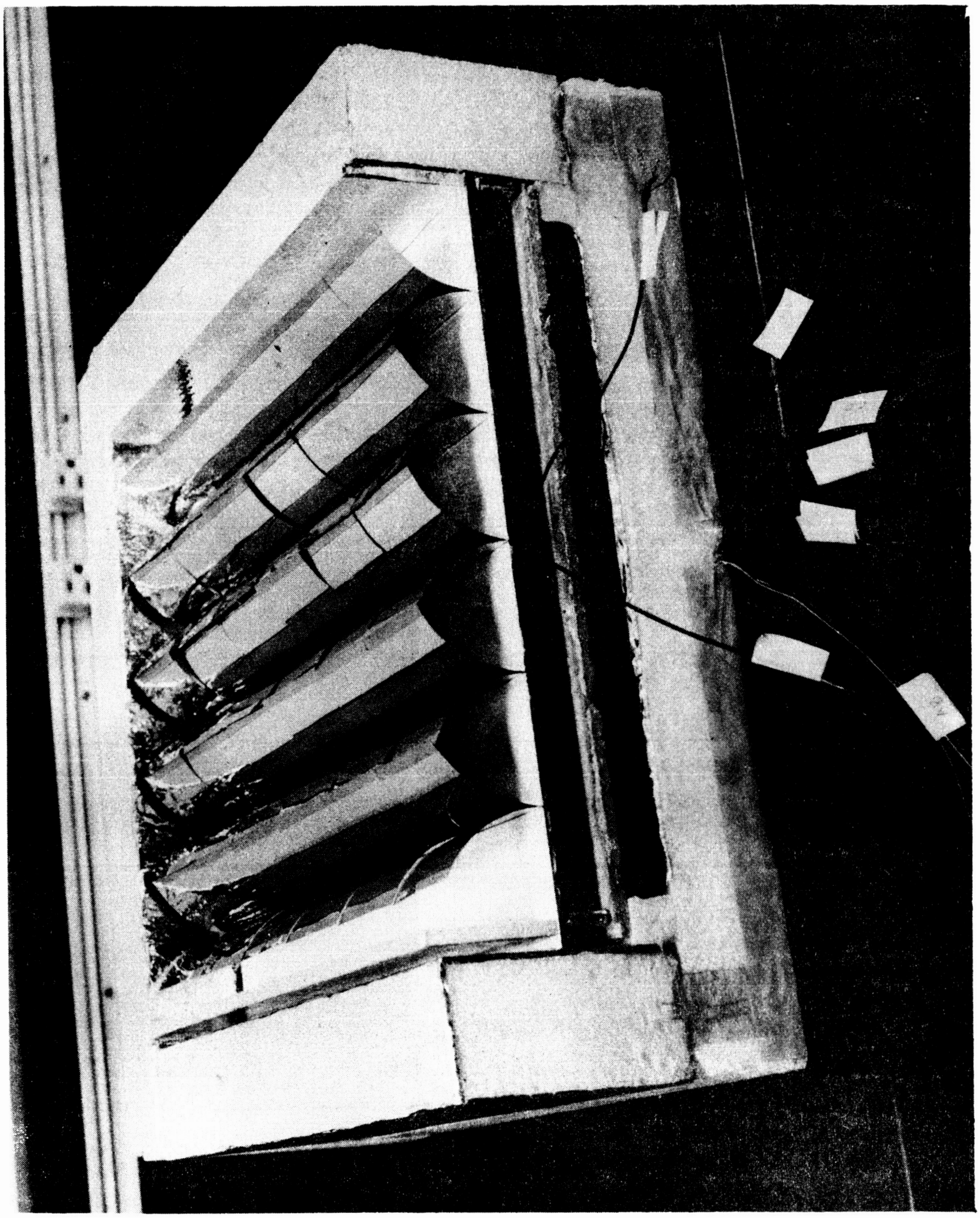

Figure 2 Test System

fin, the fin length is 2 1/16 inches of width of which the last 1/16 inch is used for mounting.

Previous investigations reported in the other two progress reports indicated that the reflectance of the high-expansion side was not as high as would be required for the simulation of the analysis; therefore, the high-expansion or manganese side of the fins was vacuum plated with a thin layer of aluminum. This aluminum overcoating was thick enough to be opaque and should result in essentially the reflectance of pure evaporated aluminum on the high-expansion side or the side facing the grooves of the spacecraft system.

The base of the spacecraft surface, a one square foot brass plate about 1/8 of an inch thick, was slotted by a milling operation with five slots two inches apart approximately 1/16 of an inch deep. Then two iron-constantan thermocouples were installed by drilling from the back as near to the exposed surface as possible. The back of this plate was coated with a highly absorbing black paint since it would receive energy from the heater plates by radiation. The front side of the plate, the outer or spacecraft surface side, was coated with Cat-a-lac white paint, No. 463-1-500. Characteristics for this exact paint were not available; however, a similar paint from the same manufacturer had been examined experimentally. The characteristics of Cat-a-lac No. 463-1-8 which were used in the analysis are shown in Figure 3. As can be seen from Figure 3, this Cat-a-lac white paint has a relatively low solar absorbtance and a high terrestrial emittance. However, it is not as good as some of the modern white paints now available. In the assumptions of the analysis for this system, it was assumed that the white base paint was a diffuse surface; however, the

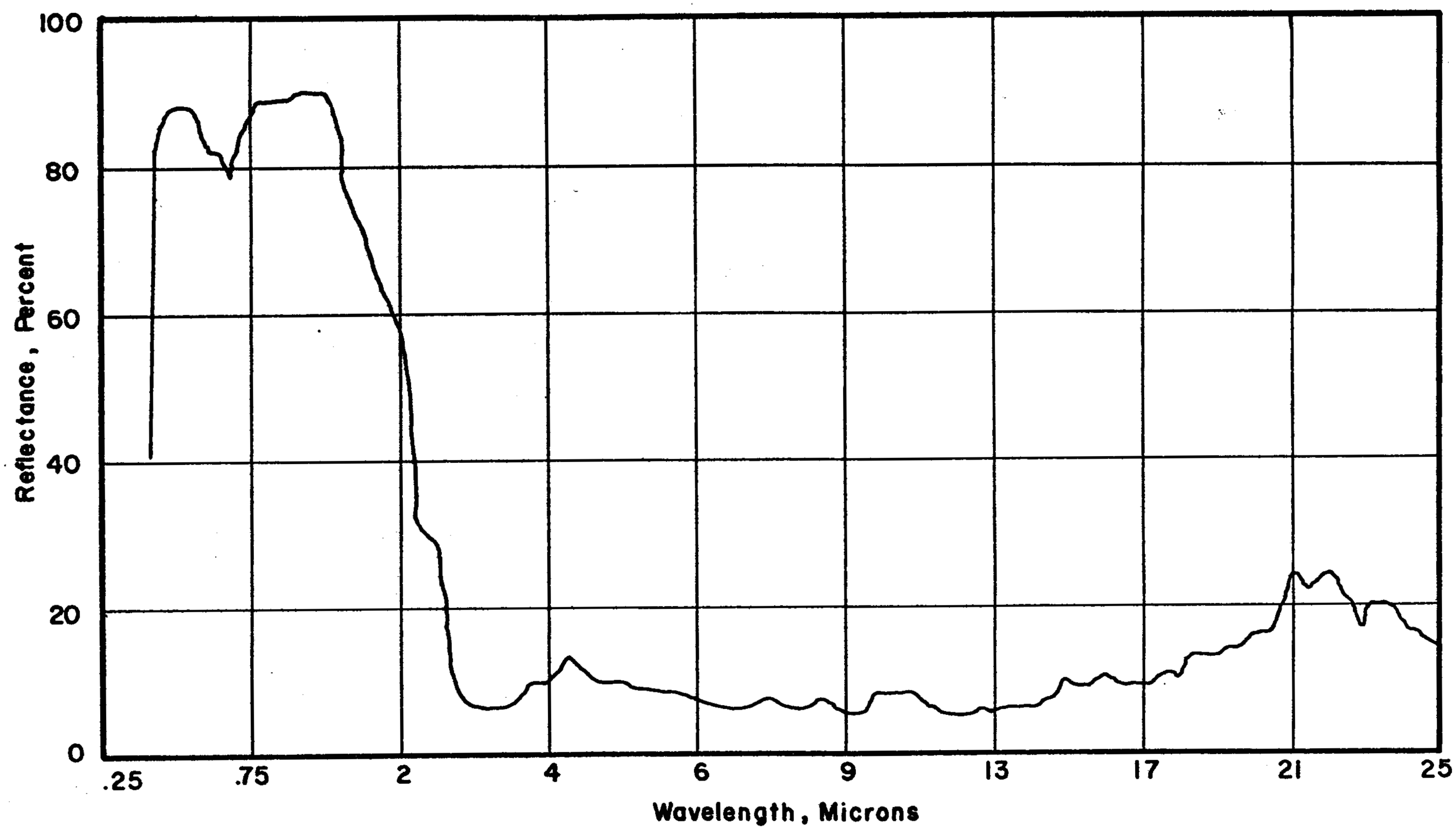

Figure 3

Monochromatic Reflectance of White Epoxy Resin Paint (Cat-a-lac) No. 463-1-8

Cat-a-lac white paint gave a slight gloss upon application. Careful sanding was used to remove this gloss, and it is assumed that this does not change the reflectance of the surface. Of course, this is not exactly true; however, the paint was not diffusing enough as applied to approximate the conditions of the analytical work. After the base plate was prepared in this manner, the fins were placed in the slots in the brass plate in their proper positions; and then a small amount of Eastman 910 adhesive was allowed to flow into the space between the fins and the slot edges. This resulted in a strong bond between the fins and the base and is the method suggested for the construction of spacecraft surfaces of this type. A picture of the completed test surface installed in a portion of the required test system is shown in Figure 2. As can be seen, the procedure used in the construction of the test surface resulted in very uniform curvature for the fins and a system which would appear to be very close to the system assumed in the analytical work.

2. CONSTRUCTION OF THE TEST SYSTEM

The basic test system is shown in Figure 4. As can be seen from this figure, the test system consists primarily of an insulated box to contain the test surface plus a heat source to simulate the internal heat generation of the spacecraft. Below the heat source a single layer of aluminum foil is used as part of a heat meter to determine the energy transferred from the heater plate through the test system other than through the test surface. The heat source consists of a piece of transite a quarter of an inch thick, one square foot in size. On the plate is wound the heater element which is

TEST UNIT (Cover Removed)

1	Vermiculite
2	Styrofoam
3	Cork
4	Aluminum Foil
5	Heater
6	Test Surface

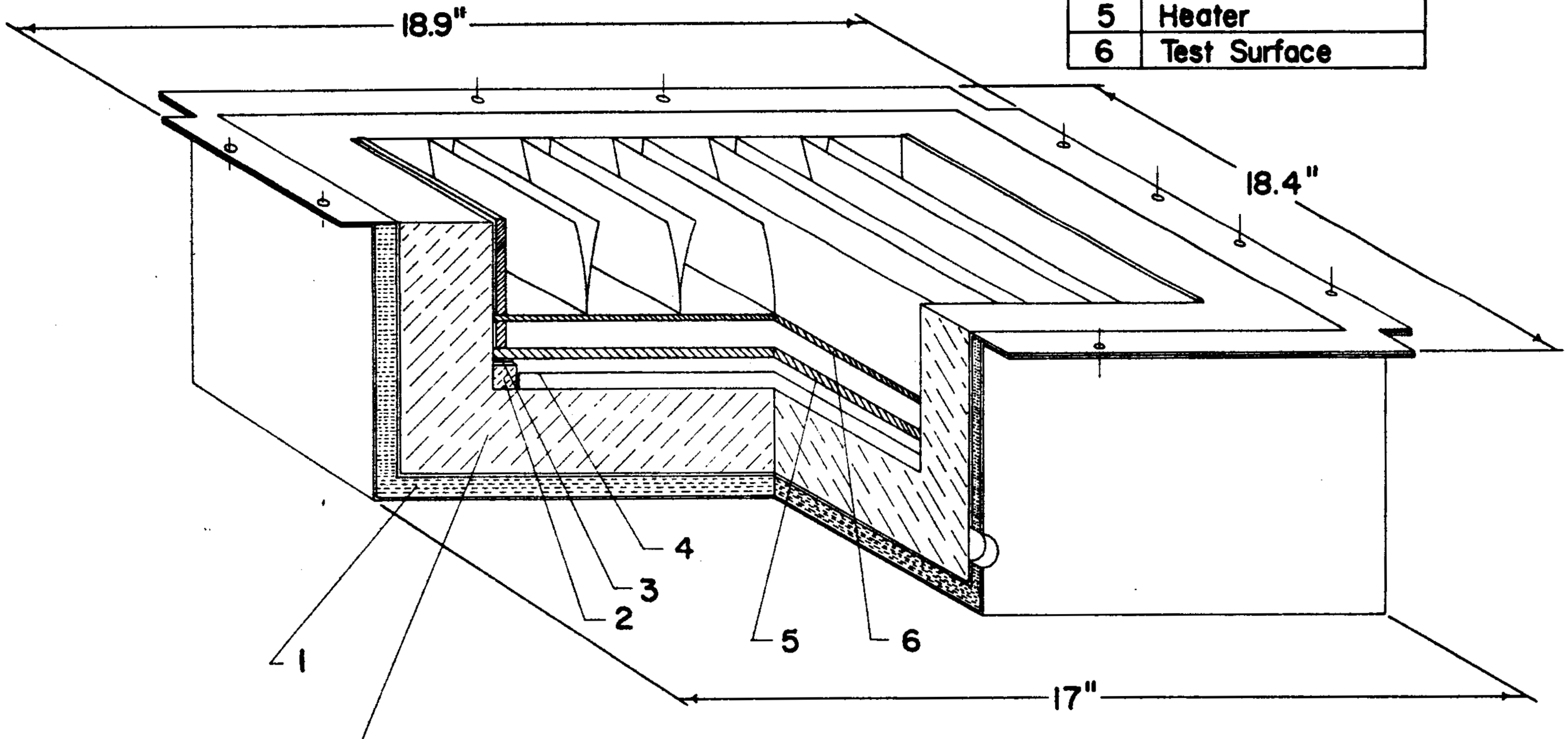

FIGURE 4

made of 30 gage Chromel A heater wire. This resistance wire was chosen such that approximately 40 watts could be dissipated when a potential of 110 volts is applied to the heater windings. The heater windings were placed on the upper face of the transite board and covered with Saureisen electrical cement. In order to control the energy input to the test surface, the heater temperature will be controlled with a proportional controller based on the temperature of the plate. A small bead thermistor temperature sensor was imbedded on the upper side of the plate and covered with Saureisen cement. In order to reduce the amount of energy lost from this plate, the entire lower section of the test system consists of rigid polystyrene blocks covered with aluminum foil. The rigid polystyrene blocks serve both to support the heater assembly and the test surface and to provide insulation between the heated section and the metal wall container for the insulation and test surface. The metal wall container consists of two separate containers with the region between the two containers filled with vermiculite powder. By placing suitable spacers, the inner and outer metal wall containers are thermally insulated away from each other. The outer surface of the metal wall container, that is the outside surface, is covered with aluminum foil cemented on with contact cement on all surfaces except for the surface presumed to be irradiated by the solar simulator. This surface is painted with Cat-a-lac white paint in order to maintain a relatively low temperature in this region.

Directly below the heater plate a single aluminum foil sheet is mounted which serves as a heat meter. This aluminum foil plate actually consists of two sheets of aluminum foil with three thermocouples connected in parallel sandwiched between the two plates, and the two plates are joined by contact cement. This aluminum foil radiation shield is directly above a styrofoam insulation block which is also covered with aluminum foil. The outer surface of the styrofoam insulator has installed in it a copper constantan thermocouple such that the the temperature of the aluminum foil covering can be determined. In the apparatus built, the spacing between the aluminum foil radiation shield and the aluminum foil on the outer surface of the styrofoam block is approximately one-half inch, and these two plates are approximately 1 square foot in size. Two parallel plates with these dimensions very nearly act as two infinite parallel plates. For this reason, the two parallel plates can be used as a heat meter. The basic idea of this heat meter is that the total energy passing in this direction away from the heater plate will be approximately 10 per cent of the total energy generated. Therefore, even though the exact emittance of the two parallel aluminum plates is not known, the estimated value of the emittances will result in energy transfer rates which are perhaps $\pm$ 10 per cent of the 10 per cent which goes in this direction. Since about 10 times more energy goes in the direction through the test section, an error of 10 per cent in the evaluation of the energy passing downward from the heater plate will result in about a one per cent error in the energy calculated as passing up from the heater plate through the test section. Since the total energy being dissipated by the heater plate is easily measured by electrical methods, the amount of energy passing upward through the test section can be determined with very good accuracy using this system.

As a matter of general interest in evaluating the energy losses from the entire test system, thermocouples are located in numerous positions around the insulating walls in order to determine the temperature differences. It is hoped that these temperatures can be used to prove the action of the heat meter system.

3. THERMAL ANALYSIS OF THE ENTIRE TEST SYSTEM

The test unit described in the previous section was examined in terms of the thermal losses which could be expected for the particular geometry. This was accomplished by examining a quarter section of the test system by means of an electrical analogy. In this analogy a thermal model of the quarter section of the test system was constructed using the typical thermal conductance and thermal capacitance technique. In the evaluation of the conductance from the various nodes, it was necessary to use radiant conductances which are a function of the temperature of the node under consideration and the node to which it was radiating. This variable conductance procedure was not immediately available to use in the system of analysis, therefore numerous approximations were made until the conductance value approached very closely the actual value indicated. In the analysis of the thermal model the main items of interest were: (1) the thermal response time of the entire system, (2) the temperature distribution in the system, and (3) the heat loss from the sides and bottom of the test unit. The boundaries assumed for the test system were a low environment temperature of approximately -360°F and a near vacuum environment. With these boundaries and the thermal model it was then possible to undertake the analysis of the system. This was done using a thermal analyzer available at Oklahoma State University which consists essentially of electrical components which can be used to approximate the thermal components. As a result of this analysis it was found that the entire test unit would have an approximate response of 63 hours. This time was so long that it was decided that the thermal equilibrium condition could not be obtained in a simulator test. For this reason the heat meter, the heater plate, and the test section itself are the only items which are assumed to come to thermal equilibrium. The test section which consists of a brass plate as indicated previously will have a response time of something less than one hour. Therefore the test procedures will not require extremely long times. Since the heat meter works entirely by radiative exchange analysis, it is not necessary for a thermal equilibrium condition to be established for any of the remainder of the system; that is, instantaneous readings of heat loss can be used when the test section itself or test plate has come to equilibrium. As an indication as to what type thermocouples to use, the steady state temperature distribution within the system was also required. These steady state temperatures are listed in Table 1 following. The final item which was required from this analysis was the determination of the heat loss from the test unit or the energy loss in the downward direction from the heater plate. When the analysis was accomplished, the single aluminum radiation shield below the heater plate was not considered to be in place. Under these conditions, it was found that the energy loss in the downward direction amounted to approximately 5 Btu per hour. With the heat shield in place, it is assumed that the energy loss will be slightly less than this amount.

The thermal analysis of the system involved estimates for the properties of the various materials involved in the test unit. The material properties used as estimates are listed in Table 2.

TABLE 1

STEADY STATE TEMPERATURE DISTRIBUTION

Node Location	Temperature ^{o}F
Heater Plate	150^{o}
Inside surface of styrofoam	
Side walls	-117
Bottom walls	-48
Outside surface of styrofoam	
Side walls	-123
Bottom walls	-59
Outside surface of test unit	
Side walls	-126
Bottom walls	-65
Chamber walls	-360

TABLE 2

MATERIAL PROPERTIES

	k $\frac{Btu\text{-}in}{hr\text{-}ft^2\text{-}F}$	ρ $\frac{lbm}{ft^3}$	c_p $\frac{Btu}{lbm\text{-}F^o}$	ϵ
Styrofoam	0.2	2.0	0.25	0.6
Aluminum Foil	-	-	-	0.05
Transite	2.4	129.0	0.2	-
Sheet Metal	300.0	487.0	0.113	0.7
Vermiculite	0.24	7.5	0.45	-
Cat-a-lac White Paint	-	-	-	0.9
Chamber Walls	-	-	-	1.0

It should be noted that several of these values could be off by a considerable amount; that is, the exact thermal conductivity of both the styrofoam and the vermiculite material are strictly estimates. More recent information indicates that the vermiculite thermal conductivity used in the analysis is quite high. For this reason it is entirely possible that the energy loss from the lower side of the heater plate will be even less than 5 Btu per hour as indicated. Of course any reduction in energy loss from the lower side of the plate results in more accuracy in the evaluation of the energy leaving the top side of the plate which is the main item of interest in the test system.

As a result of the thermal analysis it is now conceived that the testing in the thermal simulation will be as follows. First, the entire system will be mounted in the simulator at the proper solar-polar angle from the solar simulation. Before the walls are cooled or before the liquid nitrogen is introduced into the test chamber, the heater controller will be activated resulting in a certain amount of energy input to the test system. This is necessary in order to avoid extremely low temperatures in regions where materials would fail. After the simulator has been reduced in pressure and in temperature, it should require approximately one hour for the test plate to come to the thermal equilibrium value at which time the temperature of the styrofoam wall adjacent to the aluminum radiation shield would be measured. Also the aluminum radiation shield temperature and base plate temperature would be recorded. The remainder of the temperatures would be continuously recorded on multipoint recorders as check values to be used after the tests are completed. At the time that the test is taken the temperatures of the wall and the temperatures in the insulation materials will not be at equilibrium. However, the base plate itself should be at equilibrium and the heater will be maintained at equilibrium by its controller. These conditions then will result in energy measurements with little difficulty allowing the results of the next section to be checked.

4. PREDICTED RESULTS OF THE SIMULATOR TESTS

The analysis work required to predict the temperatures of the plate as constructed was carried out using the monochromatic reflectance of Cat-a-lac paint as shown in Figure 3. Basically the analysis required is an analysis to determine the temperature of the base plate as a function of solar-polar angle and energy input. This was carried out assuming that the fins would act as infinite length fins which is believed to be the closest approximation to the experimental system. This is the case because the ends of the fins are enclosed below a shielding plate. The method used in predicting the temperatures as a function of solar-polar angle and power input are basically described in the previous two reports (1, 2). As a result of this calculation the temperature of the fins as a function of the power input and the solar-polar angle is obtained. The results are shown in Figure 5. The procedure for testing the analytical results then will consist of determining the energy flow out to the plate at several different solar-polar angles and these values can be used to enter Figure 5 to obtain the predicted temperature. Since the temperature of the plate will be measured, the predicted temperature of the plate as compared to the measured temperature will result in the required comparison of the analytical and experimental methods. It should be noted that the

PREDICTED TEST RESULTS

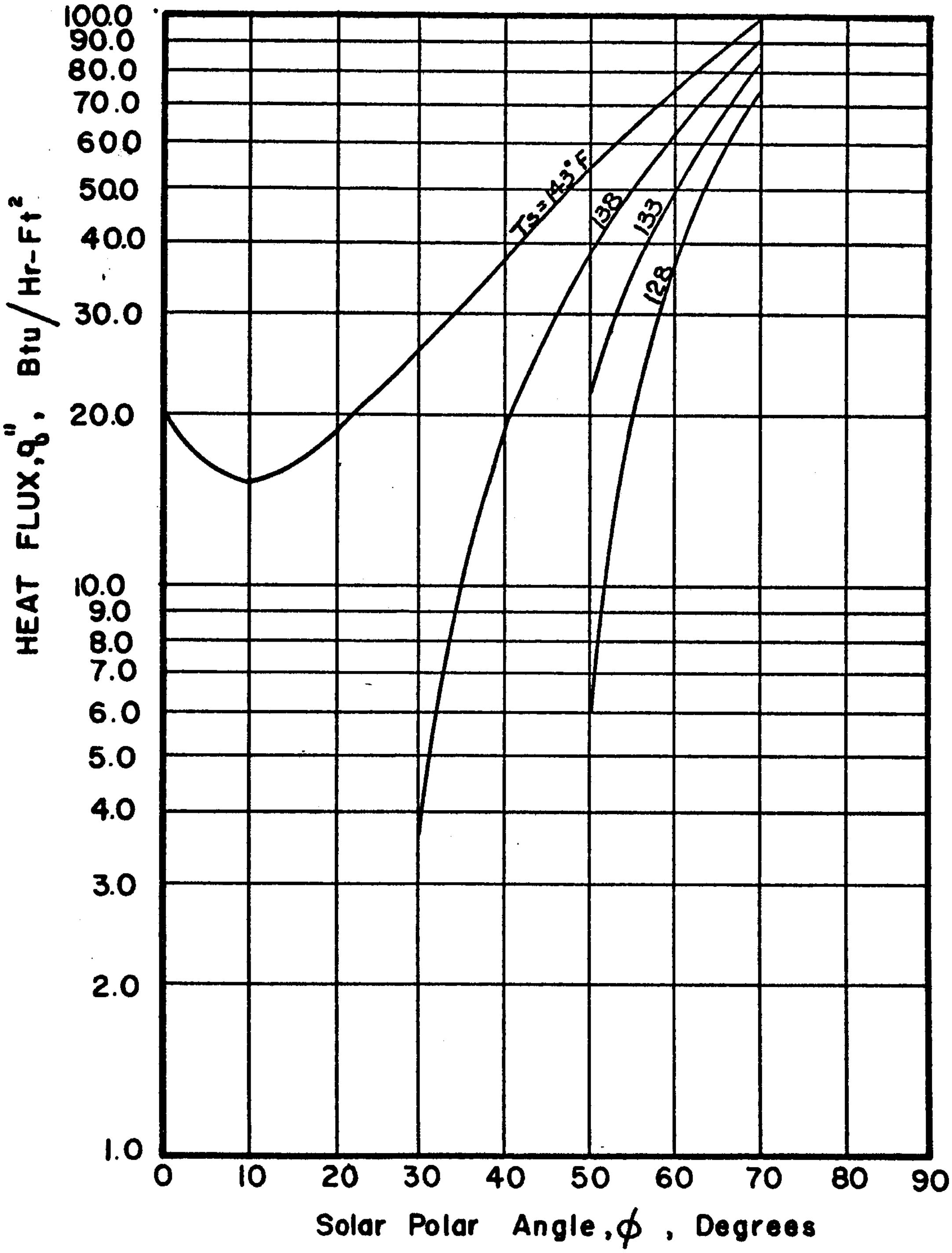

FIGURE 5

only region in which the analysis is correct is the region around 145°F. Other regions will result in fin positions other than the vertical position assumed.

5. CONCLUSION

This report consists primarily of a description of the test system and the test surface to be used in the evaluation of the analysis work done previously. The only item in the report which is unusual as far as testing procedures is concerned is the use of a radiant heat meter rather than the usual conduction heat meter. In this particular case, the energy to be measured by the heat meter does not consist of the actual energy of interest but rather the energy loss. Since the energy loss has been estimated to be about 10 per cent of the energy to be metered, the accuracy of measurement of the heat loss is much less restrictive than the accuracy required if the actual energy passing through the test system is measured. Furthermore, the use of the radiant type heat meter allows the evaluation of the energy passing through the test system without waiting for complete thermal equilibrium condition to occur; that is in this case, a local thermal equilibrium of the test surface itself will be satisfactory. This results in the test period reduction from about 60 hours to 1 hour.

It is expected that the simulation test on the spacecraft surface will be completed within a few months at the Goddard Space Flight Center. After the results of the tests are obtained, the experimental results can be compared with the analytical results with very little extra effort. Assuming that the analytical results are verified by the experimental results, the next six month period in the grant will be directed towards the reduction of the analysis procedures to a design procedure. At present it is hoped that the system can be analyzed using a solar absorptance and a terrestrial emittance value rather than having to go through the time consuming monochromatic analysis as was done in the previous section. The approach using a solar absorptance terrestrial emittance value has not been successful at present; however, it is possible that some empirical procedure can be devised using this basic idea. It is further hoped that some method may be found by which the spacecraft surface system can be flown on an actual satellite. This has been discussed with some NASA representatives, but as yet nothing concrete has been suggested.

REFERENCES

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2. Wiebelt, J. A., J. F. Parmer and G. J. Kneissl, "Spacecraft Temperature Control by Thermostatic Fins--Analysis II," Report dated June 1964 to NASA, Oklahoma State University, School of Mechanical Engineering, 1964.